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Mineral Chemistry of Volcanic Rocks of South Shetland Archipelago, Antarctica

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Abstract

This study presents the results of mineral chemistry data of Meso-Cenozoic volcanic rocks of Livingston, Robert and Ardley islands (South Shetland Arc, Antarctica). These rocks include basalts and basaltic andesites that exhibit pilotaxitic, intergranular, and intersertal textures. Glomeroporphyritic clusters consist of phenocrysts of plagioclase, augite, and Ti-magnetite or only plagioclase. The rocks are composed of plagioclase, augite, olivine, Ti-magnetite, and ilmenite phenocrysts. Geochemistry studies indicate that these rocks are rich in Al_2O_3, Rb, Ba, Sr, and show enrichment in LREE relative to HREE. The Ni, Cr, Co, and MgO contents are lower than primary compositions, and demonstrate that these magmas are evolved. Mineral chemistry indicates that the volcanic rocks belong to the calc-alkaline series typical of island arcs. Plagioclase crystals are mostly bytownite and labradorite in Livingston and Robert islands. Nevertheless, some Robert Island phenocrysts are of anorthite composition. The plagioclase of volcanic rocks of Ardley Island is only labradorite. Augite is the main mafic phase (Wo_{23-48}, En_{40-58}, Fs_{9-21}) in all studied islands. Olivine shows a chrysolite composition. Oxide phases are represented by Ti-magnetite and ilmenite. The evaluation of whole-rock geochemistry and mineral chemistry supports the hypothesis of fractional crystallization for the evolution of the rocks of Livingston, Robert, and Ardley islands. Geothermometry for olivine-clinopyroxene pairs suggests a crystallization temperature of 962°C ± 10°C (1 bar) and of 965°C ± 10°C (500 bars).

Introduction

THE SOUTH SHETLAND Islands are a mature Jurassic–Quaternary island arc built on a sialic basement of schists and deformed sedimentary rocks. Construction of the South Shetland Islands arc began during the latest Jurassic or earliest Cretaceous in the southwestern part of the archipelago. The South Shetlands Islands lie about 950 km southeast of Cape Horn and 100 km northwest of the Antarctica Peninsula, from which they are separated by Drake Passage and Bransfield Strait, respectively (Fig. 1). Geophysical evidence suggests that the islands are located on a small crustal plate, which may be defined by back-arc spreading in Bransfield Strait to the east, a well-defined oceanic trench to the west, along which subduction has apparently ceased (Barker and Griffiths, 1972).

The Livingston, Robert, and Ardley islands consist of Meso-Cenozoic volcanic rocks of basaltic and basaltic andesite composition. Andesitic, dacitic, and rhyolitic compositions are rare. These rocks are interbedded with volcanoclastic rocks such as breccias, agglomerates, conglomerates and tuffs.

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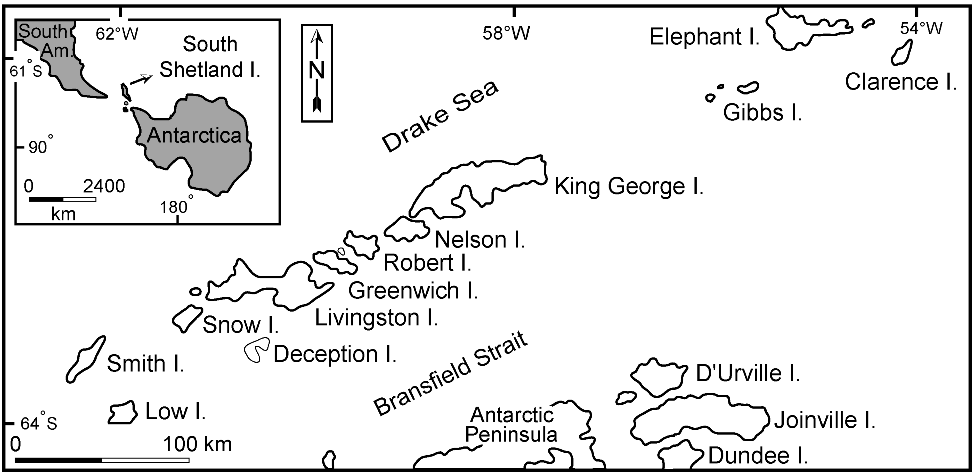

FIG. 1. Location map of the South Shetland Islands (Machado, 1997).

This paper presents and discusses the results of mineral chemistry of basic to intermediate volcanic rocks. The age of these rocks varies from 143 to 44 Ma (Pankhurst et al., 1979; Gracanin, 1983; Smellie et al., 1984; Hathway, 1997; Oteíza, 1999).

Analytical Techniques

Mineral chemistry

The mineral chemistry of plagioclase, pyroxene, olivine, and opaque minerals (samples with 277 analyzed points) was performed at Electronic Microprobe Laboratory of Federal University of Rio Grande do Sul (UFRGS) using a CAMECA SX 50 microprobe with four WDS vertical spectrometers and one EDS kevex. The correction was PAP-type. The chemistry patterns used for the calibration were Si-Anor, Ti-TiO_2, Al-Anor, Fe-MnHO, Mg-MnHO, Mn-MnHO, Ca-Anor, Na-Jade, K-Asbe, Ni-NiO, Cr-Cr_2O. The acceleration tension, current, bean diameter, and accountation points times (each chemistry element), respectively, are decrypted below for each mineral:

Plagioclase: 15 kV, 10 nA, 5 mm, Si (30 s), Al (20 s), Fe (60 s), Mg (30 s), Ca (30 s), Na (30 s), K (30 s);

Pyroxene: 15 kV, 10 nA, 1 mm, Si (30 s), Ti (30 s), Al (25 s), Fe (20 s), Mg (25 s), Mn (30 s), Ca (25 s), Na (30 s), K (25 s), Cr (30 s);

Olivine: 15 kV, 10 nA, 1 mm, Si (40 s), Ti (20 s), Al (40 s), Fe (20 s), Mg (20 s), Mn (20 s), Ca (30 s), Na (30 s), Ni (30 s), Cr (40 s);

Oxides: 15 kV, 25 nA, 1 µm, Si (30 s), Ti (20 s), Al (30 s), Fe (20 s), Mg (20 s), Mn (20 s), Ca (30 s), Ni (30 s), Cr (40 s), Co (20 s).

Whole rock

Whole-rock samples were analyzed for major and trace elements by X-ray fluorescence (XRF) at the Department of Geology and Geophysics, University of Adelaide. All samples were crushed in a tungsten carbide jaw crusher after removal of weathered rims. Loss on ignition was determined on approximately 4 g of pre-dried sample by heating to 960°C overnight. Major elements were determined on fused glass discs using a lithium meta/tetraborate flux sample: flux ratio = ¼, with a Philips PW 1480 100 kV spectrometer. Trace elements were analyzed on pressed powder pellets. Reproducibility is better than ±5%, and generally better than ±1% for major elements and around ±5% for trace elements. The accuracy of the measurements, as determined by analyses of international standards, is better than ±5% for all elements, except Ba, Ni, Zn, Cu, Cr, for which accuracy is better than ±10%. Some trace element analyses were performed at the Institute of Energetic and Nuclear Research (IPEN), São Paulo, Brazil by ICP-MS according to methods described by Figueiredo and Marques (1989). Rare earth elements were determined by ICP-MS at ACTLABS in Canada.

Petrography

Volcanic rocks

The basalts and andesitic basalts contain subhedral-anhedral phenocrysts of plagioclase, augite, olivine, and Ti magnetite set in a holocrystalline groundmass. Some plagioclase phenocrysts exhibit concentric zoning and reabsortion features (e.g., embayed rims), and range up to 3–4 mm in size. Microphenocrysts typically show similar features. Inclusions of pyroxene and magnetite are present in plagioclase. Groundmass alignments of plagioclase are well developed. Augite shows rare concentric zoning and a few twin lamellae. Augite phenocrysts are up to 2 mm in size and embayed grains are present in some samples. Olivine is typically less abundant than plagioclase and pyroxene, and generally is altered to bowlingite or iddingsite, whereas carbonate rarely is observed. Olivine phenocrysts are up to 1 mm across and microphenocrysts are generally <0.5 mm across. Abundant and partially altered phenocrysts of olivine occur in almost all basalts and basaltic andesites of Coppermine Peninsula (Robert Island), and few altered olivine crysts are present in some samples of Livingston and Ardley islands. The groundmass exhibits pilotaxitic, intergranular, and intersertal textures composed of long, lath-shaped plagioclase microlytes, augite, Ti-magnetite, ilmenite grains, and dark brown interstitial glass. Skeletal magnetite is present in some samples. Glomeroporphyritic clusters are common and are composed of phenocrysts of plagioclase, augite, and Ti-magnetite or only plagioclase, suggesting that a flotation mechanism (Campbell et al., 1978) may have controlled their distribution in the magma chamber.

Geochemistry

Whole-rock geochemistry data are listed in Table 1. Weathered rocks and rocks with high LOI were excluded from this study. All samples analyzed are subalkaline, and the majority of samples plot in the basalt and basaltic andesite field, according to the petrochemical classification of Le Maitre (2002).

The volcanic rocks have variable SiO_2 ranging from 48 to 54 wt%, Al_2O_3 from 16 to 19 wt%, and total alkali (K_2O + Na_2O) from 2 to 4 wt%. Al_2O_3, FeO_T, and CaO oxides exhibit positive correlations with MgO (4–9 wt%), implying fractional crystallization of olivine, clinopyroxene, calcic plagioclase, and Ti-magnetite. Pronounced negative Nb spikes characterize all samples, and LILEs are enriched relative to those of N-MORB. High LILE/HFSE ratios are a general feature of island arcs. N-MORB–normalized patterns for all samples are typical of subduction-altered magmas, with negative Nb and Ti anomalies, and positive spikes on K, Ba, and Sr. On average, the rocks have depleted characteristics, with N-MORB–normalized levels of Nb lower than Zr, and enrichment in light and middle REE compared to N-MORB. Some samples from Livingston, Robert, and Ardley Islands show weak positive or negative Eu anomalies, which are correlated with accumulation and fractionation of plagioclase in magma.

Mineral Chemistry

Plagioclase

Plagioclase exhibits a wide compositional range in basic and intermediate samples ($An_{48–95}$), with a maximum anorthite (An) content of 95 mol% (Table 2). Labradorite phenocrysts predominate in samples of Livingston and Ardley islands. Bytownite phenocrysts are present in rocks of Livingston and Robert islands. Labradorite and bytownite microcrysts occur in the matrix of Livingston, Robert, and Ardley islands. A few microcrysts of andesine typify samples of Ardley and Robert islands. Al_2O_3 contents vary from 26 to 36 wt%. FeO and MgO contents are <2 wt%.

Highly calcic plagioclase is common in high-Al arc basalts, with An content dependent upon the H_2O content, crystallization pressure, Al_2O_3 content, and CaO/Na_2O value of the melt (Panjasawatwong et al., 1995). Melt CaO/Na_2O exerts the strongest control on plagioclase An content, with values of CaO/Na_2O > 8 required to produce highly calcic (An_{95}). High An content is typical from island arc basalts, and it is related to high PH_2O in arc magmas.

Pyroxene

The vast majority of pyroxenes are typical augites. Chemical composition of clinopyroxene plots on the QUAD field, which groups Ca-Mg-Fe pyroxenes (Morimoto, 1988). The pyroxenes of basic and intermediate rocks show similar chemical compositions (Wo_{30-48}, En_{41-44}, Fs_{10-26}). CaO contents vary from 14 to 24 wt%. Al_2O_3 contents are between 1 and 6 wt%, and MgO from 14 to 16 wt% (Table 3). Augite is predominant in Livingston and Ardley islands as phenocrysts and grains of matrix, but the

TABLE 1. Selected Whole-Rock Analyses of Volcanic Rocks from Livingston, Robert, and Ardley Islands[1]

	Ardley Island			Livingston Island		Robert Island		
Sample:	990114001	990114006	98012002	98012202	98012702	96020701	96022001	990109001
Age, Ma:	55	55	90	75	80	80	80	60
SiO_2	53.78	51.73	49.6	48.4	50.54	48.09	49.31	49.13
TiO_2	0.98	0.8	1.31	0.91	1.1	0.97	0.89	0.95
Al_2O_3	17.14	18.15	17.3	18.29	17.03	16.93	17.5	17.64
FeO_T	9.78	9.06	11.6	9.24	9.57	9.5	9.6	9.38
MgO	4.89	5.35	4.1	7.59	8.01	8.86	8	7.76
MnO	0.15	0.16	0.18	0.16	0.18	0.14	0.17	0.16
CaO	7.53	9.92	9.3	11.51	9.65	10.03	10.82	9.65
Na_2O	3.03	2.91	3.9	2.37	2.88	2.66	2.51	3.17
K_2O	0.77	0.52	0.33	0.42	0.19	0.58	0.21	0.68
P_2O5	0.22	0.16	0.28	0.18	0.23	0.35	0.15	0.26
LOI	1.75	1.29	1.8	1.17	0.87	1.63	1.08	1.15
Total	100.06	100.06	100.5	100.25	100.25	99.73	100.24	99.90
Rb	14	11	5	5	3	13	3	14
Ba	292	233	126	295	87	327	122	302
Sr	510	587	476	574	369	538	482	557
Ni	25	27	15	15	161	154	100	104
Cr	65	66	20	115	366	455	329	339
Co	28	46	22	49	62	41	47	38
Nb	4	4	1	1	3	2	1	2
Zr	119	59	60	40	96	76	41.5	88
Y	21	16	20	10	23	17.5	16	16
Hf	3	n.d.	2	1	n.d.	2	n.d.	2.5
U	0.6	1.5	0.2	0.2	0.7	1.5	1	2
Th	2	4.5	1	1	3	2	0.5	2
Pb	7	6	5	5	4	5	2	4
Ga	20	19	17	15	16	18	18.5	19
Cu	152	129	33	57	35	108	72	73
Zn	92	77	57	53	70	71	65	62
Sc	26	28.5	31	27	28	20	27.5	20
V	284	273	273	237	235	250	270	242
Cs	3	n.d.	1	0.5	n.d.	n.d.	n.d.	n.d.
La	13.1	8	7.2	4.5	8	13.9	3	11.9
Ce	29	24	17.3	10.7	23	30.4	15	25.8
Pr	n.d.	n.d.	2.47	1.5	n.d.	n.d.	n.d.	n.d.
Nd	18	13	12.3	7.6	16	18.3	9	15
Sm	4	n.d.	3.6	2.1	n.d.	4.46	n.d.	3.87
Eu	1.25	n.d.	1.28	0.87	n.d.	1.30	n.d.	1.22
Gd	n.d.	n.d.	3.7	2.1	n.d.	n.d.	n.d.	n.d.
Tb	0.61	n.d.	0.6	0.3	n.d.	0.91	n.d.	0.55
Dy	n.d.	n.d.	3.5	1.8	n.d.	n.d.	n.d.	n.d.
Ho	n.d.	n.d.	0.7	0.4	n.d.	n.d.	n.d.	n.d.
Er	n.d.	n.d.	2	1.0	n.d.	n.d.	n.d.	n.d.
Tm	n.d.	n.d.	0.31	0.14	n.d.	n.d.	n.d.	n.d.
Yb	2.1	n.d.	2.0	0.9	n.d.	1.59	n.d.	1.70
Lu	0.29	n.d.	0.29	0.13	n.d.	0.21	n.d.	0.21

[1]n.d. = not determined

TABLE 2. Representative Plagioclase Analyses[1]

	Ardley Island		Livingston Island			Robert Island		
Sample:	990114001F	990114001M	98012101M	98012101F	98012101M	96020701F	RO-145.1M	RO-145.1F
SiO_2	54.17	57.55	55.55	50.08	54.66	47.99	54.94	45.62
Al_2O_3	28.88	26.40	28.66	31.98	29.04	32.97	28.72	35.67
FeO	0.88	1.48	0.87	0.89	1	0.86	0.71	0.38
MgO	0.13	0.11	0.13	0.07	0.09	0.06	0.00	0.01
CaO	11.93	9.27	11.58	15.23	12.11	16.57	11.70	19.62
Na_2O	3.93	5.17	4.54	2.48	4.22	1.81	4.32	0.44
K_2O	0.23	0.50	0.12	0.06	0.17	0.05	0.16	0
BaO	0.15	0.09	0	0	0.03	0	0	0.04
Total	100.30	100.57	101.45	100.79	101.32	100.30	100.55	101.78
An	62	48	58	77	61	83	59	95
Ab	37	49	41	22	38	16	40	4
Or	1	3	1	1	1	1	1	1

[1]F = phenocryst; M = grain of matrix.

TABLE 3. Representative Pyroxene Analyses[1]

	Ardley Island	Livingston Island			Robert Island		
Sample:	990114001F	98012607M	98012101M	98012101M	96020701F	96020701F	96020701F
SiO_2	51.84	52.52	53.16	51.91	52.14	51.99	49.29
TiO_2	0.75	0.70	0.80	0.81	0.64	0.58	0.49
Al_2O_3	1.77	1.65	2.07	3.12	3.02	3.16	5.56
FeO	15.34	12.98	10.52	9.37	5.67	5.86	3.02
Fe_2O_3	0.30	0	0.00	0.74	0.90	1.05	2.65
MgO	15.24	14.28	15.50	14.79	15.28	15.45	14.59
MnO	0.47	0.33	0.26	0.25	0.27	0.14	0.12
CaO	14.76	18.26	19.24	19.97	22.12	21.86	23.17
Na_2O	0.17	0.20	0.18	0.27	0.30	0.25	0.12
Cr_2O_3	0.01	0	0.02	0.14	0.41	0.37	0.82
Total	100.63	100.92	101.83	101.35	100.74	100.70	99.82
Wo	30	39	39	41	45	45	48
En	44	41	44	42	44	44	42
Fs	26	20	17	17	11	11	10

[1]F = phenocryst; M = grain of matrix.

phenocrysts in Livingston Island have a tendency to be more calcic. Robert Island exhibits two fields for pyroxene; the first one shows phenocrysts and matrix grains more calcic, with augite and diopside compositions, and the second contains only matrix grains with augite compositions, and the grains plot close the limit line between augite and pigeonite (Fig. 2).

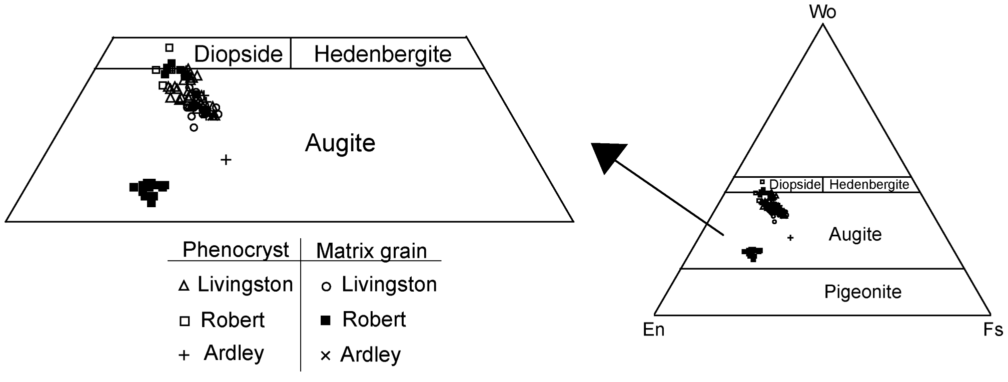

Fig. 2. Pyroxene classification diagram (Morimoto, 1988).

Olivine

Fresh phenocrysts of olivine are only present in Robert island samples. Olivine shows a chrysolite composition; a few grains plot in the hyalosiderite. Forsterite (Fo) contents of olivine phenocrysts range from Fo_{71} to Fo_{82} , with considerable variation, typically on the scale of individual samples. CaO contents do not exceed 1 wt%, which is a typical value for basaltic olivines (Jurewicz and Watson, 1988). NiO and Cr_2O_3 are low (<1 wt%) (Table 4).

Oxides

The oxide phase belongs to the FeO-Fe_2O_3-TiO_2 system and is represented by Ti-magnetite and ilmenite. TiO_2 content in the Ti magnetite varies from 11 to 27 wt%, and in the ilmenite from 45 to 48 wt%. Cr_2O_3 content is between 0.1 and 2 wt%, whereas the MnO is less than 5 wt% (Table 5).

Geothermometry

The crystallization temperature of basaltic rocks of South Shetland, Antarctica was calculated only for Robert Island. Ilmenite-magnetite (thin section 960220701) and olivine-clinopyroxene (thin section 960220701) pairs were processed through the CaQuilf software (calcic-pyroxene-quartz-ulvospinel-ilmenite-fayalite) of Frost and Lindsey (1992, version 6.42). According to these authors, we have considered the following aspects in the chosen analyses: (a) the mineral pairs used suggest equilibrium conditions and do not exhibit petrographic features of reaction, reabsortion, and zoning; (b) the equilibrium was apparently maintained after crystallization and exsolution features were not evinced; (c) the obtained analyses were within uncertain limits of pyroxene compositions, specially the Fe^{+3} content in pyroxene.

The chosen pyroxenes and magnetites are microphenocrysts, which allowed fixing the pression from 1 to 1500 bar with intervals of 500 bars, according to Frost and Lindley's suggestion (1992). Chemical data for the olivine-clinopyroxene pair suggest a crystallization temperature of 962°C ± 10°C (1 bar) and of 965°C ± 10°C (500 bars). The obtained temperature and the degree of uncertainty suggest that the olivine and the augite remained close to equilibrium in the basaltic rock. In a second geothermometry test, we used the compositional data of the ilmenite-magnetite pair within the same interval of pressure used in the first test. The equilibrium-obtained temperatures were of 745°C (1 bar) and 747°C (500 bar) to an equal uncertainty degree. Afterwards, we fixed the composition of three phases (olivine + augite + ilmenite), obtaining temperature values of 946 ± 59°C (1 bar) and 948°C ± 54°C (500 bar). The results suggest a re-equilibrium in the temperature of the ilmenite-magnetite pair, thus increasing the degree of uncertainty of the crystallization temperature of olivine-clinopyroxene-ilmenite.

Discussion

The samples of all islands show elevated Al_2O_3 (16–19 wt%) and variable MgO content (4–9 wt%). Ni and Cr values are low, which classifies the samples as non-primary. Only some samples from Livingston and Robert Island have high Ni and

TABLE 4. Representative Olivine Analyses from Robert Island[1]

Sample:	96020701F	96020701F	96020701F	96020701F	96020701F	96020701F	96020701F	96020701F	96020701F
SiO_2	38.12	37.85	38.02	37.98	39.01	38.43	38.84	39.97	39.29
TiO_2	0.01	0	0.04	0.03	0.06	0.02	0.02	0	0
Al_2O_3	0.03	0.02	0.02	0.04	0.02	0.02	0.05	0.04	0.03
FeO	22.76	24.24	25.81	22.35	23.39	25.46	21.43	16.59	20.58
MgO	37.72	36.36	35.91	38.11	38.07	36.48	38.76	43.29	40.36
MnO	0.42	0.46	0.46	0.34	0.35	0.49	0.33	0.26	0.31
CaO	0.22	0.22	0.17	0.19	0.20	0.23	0.22	0.16	0.17
Na_2O	0	0	0	0	0	0	0	0	0
K_2O	0	0	0.02	0	0.01	0	0	0	0
NiO	0.09	0.10	0.06	0.06	0.12	0.12	0.20	0.14	0.14
Cr_2O_3	0.06	0	0.02	0.07	0.02	0	0.11	0.02	0
Total	99.42	99.24	100.52	99.17	101.25	101.25	99.96	100.47	100.89
Fo	75	73	71	75	74	72	76	82	78
Fa	25	27	29	25	26	28	24	18	22

[1]F = phenocryst.

TABLE 5. Representative Oxides Analyses[1]

Sample:	Ardley Island			Livingston Island			Robert Island		
	990114001M	990114001M	990114001M	98012101F	98012101F	98012101F	96020701M	RO-145.1F	RO-145.1F
SiO	0.14	0.21	0.12	0.90	0.40	0.34	0	0.04	0.03
TiO_2	18.45	13.39	14.28	19.32	15.77	26.76	45.58	47.52	45.61
Al_2O_3	1.83	0.09	3.08	0.77	3.90	1.29	0.05	0.01	0.02
FeO	46.56	43.04	43.70	15.04	14.29	21.57	36.95	47.28	36.79
Fe_2O_3	26.92	37.23	34.55	61.49	61.04	45.75	14.27	0	12.46
MgO	0.01	0.06	0.01	0.23	0.89	0.06	2.01	0.03	0.11
MnO	0.13	0.10	0.12	2.46	1.87	3.60	0.50	3.66	4.02
CaO	0.11	0.01	0.02	0.13	0.08	0.07	0.04	0.14	0.05
Cr_2O_3	0.25	0.49	0.96	0.05	1.79	0.73	0.05	0.02	0.05
Total	94.40	97.60	96.82	100.41	100.11	100.18	99.44	98.68	99.13

[1]F = phenocryst and M = grain of matrix.

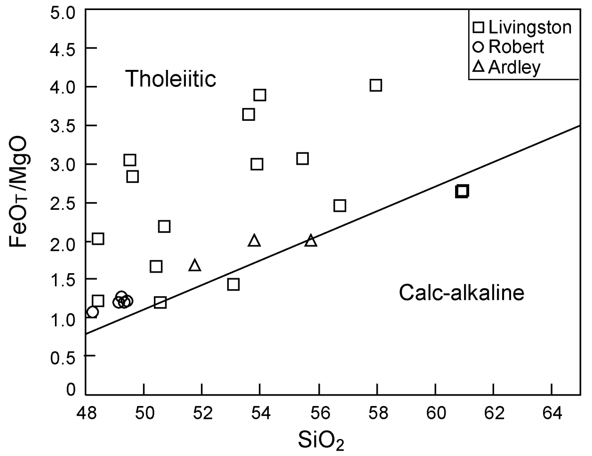

Fig. 3. $SiO_2 \times FeO_T/MgO$ diagram.

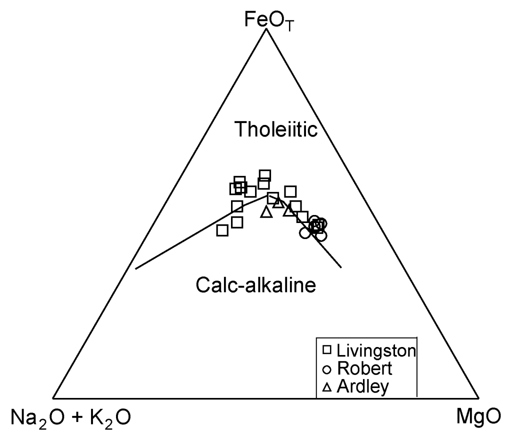

Fig. 4. AFM diagram showing the South Shetland samples distribution (calc-alkaline and tholeiitic fields from Irvine and Baragar, 1971).

Cr, which are probably due to the result of olivine accumulation.

The enrichment in LILE cannot be explained without invoking metasomatic modification of the depleted mantle source by subduction fluids. In contrast to the LILE, the HFSE such as Zr, Hf, Ti, and Nb are relatively insoluble in aqueous fluids (Keppler, 1996). In island arcs, therefore, these elements are predominantly derived from the mantle wedge, and their relative concentrations reflect the composition of the mantle wedge beneath the arc.

As it is commonly observed in subduction-related volcanic rock classification (Vukadinivic and Sutawidjaja, 1995), the use of different parameters to categorize the South Shetland samples show contradictory results. On an $FeO_T/MgO \times SiO_2$ diagram (Fig. 3), the South Shetland samples straddle the tholeiitic–calc-alkaline boundary, with a definite tholeiitic trend, showing marked Fe enrichment. This is contrary to the AFM diagram (Fig. 4). The geochemistry patterns of the South Shetland Islands suggest gradual modification of the source by subduction components. These modifications were responsible for the tholeiitic evolution to calc-alkaline. The calc-alkaline affinity is confirmed by the LILE enrichment and low Nb, Zr, and TiO_2 contents. The mineral chemistry data are also compatible with calc-alkaline series (Ewart, 1982; Machado et al., 2001).

The mineral chemistry of basic and intermediate rocks shows an association of Ca-plagioclase (bytownite) + augite ± olivine + magnetite. Ca-plagioclase composition and concentric zoning are typical of the low-K and calc-alkaline series.

Conclusions

Labradorite and bytownite are the phenocrysts and microcrysts of plagioclase predominant in the studied volcanic rocks. Augite is the main pyroxene found in the samples, but Robert Island also shows phenocrysts and matrix grains of diopside. The fractional crystallization of olivine, clinopyroxene, calcic plagioclase, and Ti-magnetite was the magmatic process responsible for chemical evolution of the South Shetland rocks. Samples from Livingston and Robert islands show high Ni and Cr contents, which reflects olivine accumulation. The volcanic rocks show calc-alkaline affinities according to whole-rock geochemistry and mineral chemistry data. The results of geothermometry tests show that the olivine and the augite remained close to equilibrium in the basaltic rock and suggest a subsolidus re-equilibrium in the temperature of ilmenite-magnetite pair.

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